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ScienceDirect
JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2016, 23(1): 53-56

Critical Shear Offset of Fracture in a Zr-based Metallic Glass

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Abstract: The nanoscale shear band operation process of $Zr_{55}Pd_{10}Cu_{20}Ni_5Al_{10}$ metallic glass (MG) was reined in by constant force during well-designed loading-holding-unloading cyclic microcompression test. Through the test, it is revealed that the whole shear banding process involves three stages: shear band initiation, shear sliding and shear band arrest. Based on the energy balance principle, the size-affected speed of shear sliding is interpreted. The energy originated from the shear sliding leads to heat-up of the shear plane; therefore, the temperature in shear band increases with the size of shear offset caused by the energy accumulation during shear sliding. Taking the glass transition temperature as the critical temperature of fracture for the Zr-based MG, the critical shear offset is predicted to be approximately 190 μm, fully in line with the experimental observation. This directly proved that the fracture of the MG is caused by the temperature rise during shear sliding.

Key words: metallic glass; shear band; fracture; temperature rise

Metallic glasses (MGs) exhibit numerous desirable mechanical and physical properties, such as ultra-high strength, large elastic limit, excellent corrosion resistance, extremely low magnetic loss and so on, therefore, they have been attracting great interests from scholars in the research community[1-3]. However, the plastic deformation of MGs takes place in the form of localized shear band, and catastrophic failure ensues immediately with the crack initiating from the shear band sites, which severely hinders the application of MGs[4]. Therefore, the understanding of failure mechanism is crucial for improving the plasticity of MGs. Lots of works have been performed to study the shear band of MGs[5-8]. Generally, it is believed that the shear band nucleates through activation of free volumes or shear transformation zones, accompanied by local volume dilation and shear softening. To a percolation point, the embryonic shear band penetrates through the whole sample instantaneously with the speed at the order of sound velocity and forms the mature shear band[9]. Along the shear plane, upper and lower parts of the MG samples slide with gradually increasing speed[10]. The external appearance of shear band is localized band region with thickness of about 10 nm and length in the dimension of the sample size. Micrometer scale shear offset generally serves as the manifestation of shear band and has attracted a plenty of interests, partially because it is an easily quantifiable parameter for measurement[11]. Wu et al.[7] reported that the critical shear offset is the critical condition for the failure of MG using small punch tests, and they interpreted the critical shear offset might be attributed to the temperature rise inside the shear bands. And they have also proposed that the critical shear offset could be used to interpret the shear deformation abilities of MGs[12]. However, the physical mechanism of the critical shear offset has not been clarified yet.

During shear banding, the temperature in shear band will increase due to the energy dissipation[13]. Using an ingenious fusible-coating method, Lewan-

Foundation Item: Item Sponsored by Natural Science Foundation of Guangdong Province of China (2014A030310189); Shenzhen Senior Talent Research Start-up Funding of China (827000056); General Research Fund from Research Grant Council of Hong Kong Government of China (CityU 102013)

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dowski and Greer[5] found that there can be a remarkable temperature rise up to a few thousand Kelvin in shear band. Different from this result, it is also demonstrated that the temperature rise in shear band may be only a few degree centigrade based on the serration in compression test[14]. And recently, it is revealed that the temperature rise in shear band is size dependent[15]. Although lots of studies have been performed about the heating in shear band, direct evidence of the failure mechanism is not clear yet. In this study, based on the temperature increasing with shear offset, the authors successfully reveal that the failure of MGs is due to the temperature rise in the shear band reaching the glass transition point, where the shear band loses its ability to recover and sustain further plastic flow.

1 Experimental

In order to fabricate MG with fully amorphous structure, the Zr-based alloy ingots with the nominal chemical composition of $Zr_{55}Pd_{10}Cu_{20}Ni_5Al_{10}$ were prepared by arc-melting high-purity raw metals of Zr, Pd, Cu, Ni and Al at least five times to ensure fully uniform mixture. Then, bulk MG rods with diameter of 5 mm were suction casted, and the glassy structure of the alloys was confirmed by X-ray diffraction (XRD). Before focused ion beam (FIB) milling, the MG was polished to a mirror finish with 0. 2 μm polishing suspensions. On the surface of polished Zr-based MG, micropillars with diameter of about 1 μm and height of about 2 μm, shown in the inset of Fig. 1, were milled out utilizing FEI Quanta 200 FIB equipment[16]. Afterwards, microcompression was conducted based on the HysitronTM TI950 nanoindentation system, which has ultra-high resolutions (around 1 nm in displacement and around 1 μN in load), to reveal the details of the deformation process.

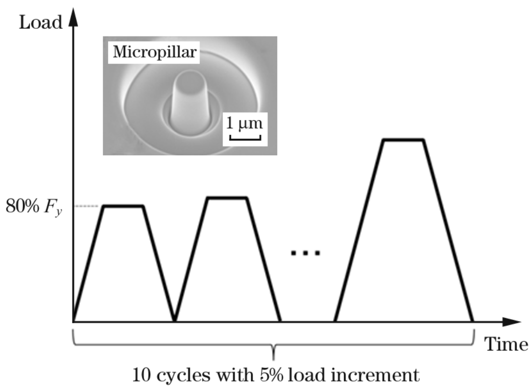

Fig. 1 Cyclic loading-holding-unloading microcompression program with the appearance of one typical micropillar

Different from the conventional monotonous loading program, a multiple loading-holding-unloading procedure was carefully designed to retard shear band operation by the holding load with a little energy input in 2 s, as shown in Fig. 1. The initial force was set to start from 80% of yielding strength (2 GPa) of the Zr-based MG and increase with a 5% increment in the subsequent 9 holding segments. Utilizing this well-designed cyclic loading program, sufficient shear band events can be detected in each micropillar, and plenty of data can be obtained for the subsequent analysis.

2 Results and Discussion

A typical shear band event during the holding stage is shown in Fig. 2. It displays that a displacement jump (or pop-in) takes place abruptly after the nearly flat creep stage in the depth-time curve, which is significantly different from traditional shear band operating process manifesting as serrations under monotone increasing load. This is because the shear banding process has been restrained by the constant load with little energy input in the holding stage; therefore, the details of shear band event can be readily revealed. It indicates that the shear band operation process involves three stages: shear band initiation, shear sliding and final shear band arrest (as shown in Fig. 2). In the initiation stage, the depth of the indenter stays almost constant with tiny amount of increase; nevertheless, the internal atomic scale damage sites (liquid like cores or flow units) are driven to a percolation point and form the shear band embryo; meanwhile, the viscosity of the MG drops from infinite to the value at an order of glass transition point[17]. Then, the embryonic shear band loses its stability, with released energy softening a plane to supercooled liquid state, and forming the mature shear band[9]. Along the mature shear plane,

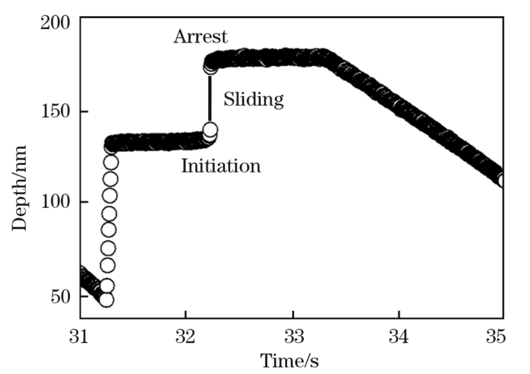

Fig. 2 Typical shear banding event occurring during holding stage